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The Biochemical and Physiological Effects of 95 Days Endurance Exercise in Negative Energy Balance

by

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INTRODUCTION

In times of war, men push themselves to physical limits well beyond those that are conventionally thought possible, and hence it is extremely difficult to predict the limits of endurance capabilities using laboratory based studies. Of course, studies can be performed examining military exercises, although motivation levels may not be maximal and it is perhaps better to study rigorous military selection processes, where intense competition maximises the psychological drives. This approach has been utilised successfully by several groups. For shorter-term activities, it is also possible to study athletic performance which provides measures of sustainable levels of physical effort with some degree of military relevance, since athletes are very highly motivated. In the case of ultra-distance competitors, there is even the potential to assess physical performance and its decline over several days, and hence studies of these events should be encouraged in the context of furthering our understanding of exhaustive military Operations. However, when it comes to investigation of likely physical performance over very extended exhaustive activities, it becomes increasingly difficult to find potential study models which combine sustained physical work with the kind of motivation levels that would occur in potential life threatening wartime situations. It is in this context, that I believe that studies of prolonged Polar, or other expeditions can be of value.

Polar expeditions provide an opportunity to examine the effects of extreme sustained exercise combined with relative under nutrition in an adverse environment. The participants are pushed to their physiological limits and hence the data gathered can provide unique information regarding survival and function under the very worst conditions. This paper describes studies performed in relation to the first unsupported crossing of Antarctica - studies conducted by the Army Personnel Research Establishment, UK, which is now incorporated into the DRA Centre for Human Sciences.

THE EXPEDITION

In November 1992, two men (RF and MS) set off from the Atlantic coast of the Antarctic aiming to perform the first crossing of the continent unaided by other men, animals or machines. Each man pulled a sledge weighing 222 kg which contained 100 days of food, fuel and other essential survival equipment. They hauled the sledges for between 10 and 12 hours daily, initially for 20 days across the 350 km Filchner ice shelf (a region of glacial ice floating on the sea or grounded on the sea bed) before they met the Antarctic coast. There then followed a 340 km ascent to the Polar plateau at 3000m and 550 km across the plateau to reach the South Pole on day 68. Beyond the Pole, the men travelled a further 480 km on the plateau, before descending through the Trans-Antarctic mountains to reach the Pacific coast of Antarctica and the Ross ice-shelf on the 90th day of the journey. An attempt to cross this second ice-shelf, to reach the open Pacific ocean, was abandoned on day 95 when it became evident that the men were suffering from severe malnutrition. The expedition was the first to complete a crossing of the Antarctic mainland without the use of aircraft to ferry food and equipment, and at nearly 2300 km was the longest unsupported walk ever made. Still air temperatures ranged from $-45^{o}C$ to $-10^{o}C$ often accompanied by high winds (Stroud, 1993).

The choice of diet during the expedition was critical. Work performed on a previous expedition of similar nature showed that daily energy expenditure when manhauling in Antarctic conditions was likely to be around 25 MJ.day^{-1} (Stroud, 1987). An intake that provided 23 MJ.day^{-1} was therefore planned, with an acceptance that weight losses over the planned 100 day journey would be around 10 kg. Of course, the nature of our journey dictated that the food should weigh a minimum and hence should contain as high a fat content as possible. However, this requirement conflicted with that of achieving maximal glycogen resynthesis at the end of each day, for although the exertion was essentially of low intensity in physiological terms, it would still lead to marked glycogen depletion by the end of 10 to 12 hours of exertion. In the end, a compromise daily diet containing 23 MJ as 57% fat, 35% carbohydrate and 8% protein was selected, a decision supported by the successful use of a similar diet on the earlier expedition Stroud, 1987). There is also evidence to suggest that man can adapt to a high fat intake and improve muscle utilisation of free fatty acids (French et al, 1993; Phinney et al, 1983). Eventually, however, the planned diet was not adhered to since, after leaving the Pole, debilitation from a continued energy deficit became severe. The men therefore increased intakes to around 28 MJ.day^{-1} until Day 84 when they commenced their descent from the plateau down the Beardmore glacier. They then reduced their intake to just 16MJ.day^{-1} in the hope the excess food consumed could be recovered and the overall 100 day range regained.

AIMS OF RESEARCH

The expedition afforded an opportunity to examine energy balance over a prolonged period of heavy work in a cold environment and to study the associated changes in body composition, resting metabolism and metabolic responsiveness to food. Subject numbers were obviously limited to only 2 individuals and logistic considerations also limited the scope and detail of the work that could be carried out. However, the following studies were performed:

a) Body weight and composition changes.

b) Energy expenditure using dietary intake/weight losses and the isotope-labelled water technique.

c) Resting metabolic rates and metabolic and biochemical responses to a high fat test meal before and after the expedition.

d) Maximal aerobic capacity and isometric muscle strength before and after the expediton.

e) Skeletal muscle enzyme activity before and after the expedition.

f) Changes in biochemical parameters at during the course of the expedition.

METHODS

Subjects. The two men, RF and MS, were well trained. Their age, weight, height and maximal oxygen uptake (VO2max.) prior to the experiment were 48 and 37 yr, 95.6 and 74.8 kg, 188 and 169 cm, and 53.6 and 58.1 ml O2 kg-1.min-1, respectively. Informed written consent was obtained prior to the experiments.

a) *Body weight and composition changes*

Body mass was recorded in the UK 10 days prior to and 6 days after the expedition and, in addition, was recorded at the start and finish of the journey using a miniature load-cell based portable scale (Miniscale, Raviv-Aran, Israel). On each occasion, measurements were made after an overnight fast, defaecation and the voiding of urine. At the same time as the UK weighings, body composition was measured using underwater weighing (UWW), with measurements of residual lung volumes being made using helium dilution spirometry. No accurate food intake data were available for the periods between the UWWs and the expedition itself.

b) *Energy expenditure using dietary intake/weight losses and the isotope-labelled water*

During the experiment, the subjects ate a high-fat, energy dense (21.3 MJ.day^{-1}) diet consisting of freeze-dried meals supplemented with butter, chocolate bars, biscuits, soups and hot chocolate drinks. Dietary analysis was performed before departure with food values taken from tables (Paul and Southgate, 1978) and

from manufacturers' nutritional information. Since the food was weighed and pre-packaged into daily ration bags, and no food was left uneaten, accurate daily energy intakes could be calculated. Daily energy expenditure was then estimated by combining the daily intake figures with energy deficits calculated from the overall losses of lean tissues and fat. Lean tissue losses were assumed to be 73% water whereas fat losses were considered to be 100% fat. The calorific value of protein was taken as 18.39 kJ.g^{-1} and fat was taken as 39.7 kJ.g^{-1} (Brouwer, 1965).

Estimates of energy expenditure were made using the $^2H_2$ ^{18}O method (Prentice, 1990) modified to account for changes in likely background levels in the Polar snow water source (Stroud et al, 1993). Body isotope disappearance was followed by daily collection and later analysis of 2ml urine samples. Each subject had two determinations of energy expenditure, one between days 1 and 50 and the other between days 51 and 95.

c) *Resting metabolic rates and metabolic and biochemical responses to a high fat test meal before and after the expedition*

Following a standardised day's intake (12.0 MJ containing 35% fat, 53% carbohydrate, and 12% protein) and an overnight fast, indirect calorimetry was used to measure resting metabolic rate (RMR) 14 days prior to departure and 7 days after completion of the expedition. Following the measurements, subjects consumed a test meal of 4.8 MJ containing 55% fat, 10% protein and 35% carbohydrate. RMR measurements were then repeated at 15 min intervals for 120 min. Venous blood samples were taken prior to the meal and then at 15 min intervals for 60 min and 30 min intervals for the subsequent 300 min. The blood was analyzed for glucose, insulin, triglycerides and free-fatty acids.

d) *Maximum aerobic capacity and isometric muscle strength before and after the expedition*

Maximal oxygen uptake was measured from Douglas bag collections made during treadmill running using a continuous incremental exercise protocol. Dominant maximal voluntary contraction (MVC) force production was measured under isometric conditions in the muscle groups involved in elbow flexion, elbow extension, abdominal flexion, and leg extension using a Hermansen isometric rig (Hermansen et al, 1972), and for hand grip (Digimeter, MIE, UK) and an upright pull (Takei, Japan) using specialised dynamometers.

e) *Skeletal muscle enzyme activity before and after the expedition*

Ten days prior to the expedition and 6 days following its completion, muscle biopsy samples were taken from vastus lateralis using the percutaneous needle biopsy technique described by Bergström (1962). Samples were immediately frozen in liquid nitrogen and subsequently freeze-dried. The muscle samples weighing approx. 15 mg dry were dissected free from visible blood and connective tissue, and powdered before being homogenised and the enzyme activities determined for four different enzymes, chosen to be representative of different components of muscle energy metabolism (Wibom et al, 1992): Glyceraldehyde-3-phosphate dehydrogenase (Gly3PDH) from glycolysis; ß-hydroxyacyl-CoA dehydrogenase (HAD) from ß-oxidation of free fatty acids, citrate synthase (CS) from the citric acid cycle; and cytochrome-c oxidase (COX) from the electron transport chain.

f) *Changes in biochemical parameters at during the course of the expedition*

At 10 day intervals during the experiment, blood samples were taken to assess hormonal and biochemical responses. Venepuncture was performed approximately 30 min after the end of the daily 10 to 12 hours of exercise and at least 4 hours after the last food intake. The samples were collected into tubes containing fluoride oxalate which were then hung in the roof of the tent for 2 to 3 hours to allow partial red cell sedimentation. A small plasma sample of between 0.5 and 1.0 ml was then pipetted off and allowed to freeze. Following the experiment, the frozen samples were returned to the UK where standard enzymatic and radio-immuno assays were used to assess glucose, insulin, growth hormone (GH), cortisol, testosterone, luteinizing hormone (LH), thyroid function, cholesterol, triglycerides, total protein and albumin.

RESULTS

a) *Body weight and composition changes*

Following the adjustments to rations during the journey, the average the diet over the whole expedition provided 21.6 MJ.day-1 of which 56.7% came from fat, 35.5% from carbohydrate, and 7.8% from protein. Despite this intake, weight losses were severe (Table 1) and both men became severely debilitated.

Table 1. Body weight and composition pre and post expedition

Age		Body weight (kg)		% fat UWW		Weight	Fat	FFM
Subject	(yrs)	Pre	Post	Pre	Post	Loss	loss	loss
RF	48	95.6	71.0	19.0	1.9	24.6	16.8	7.8
MS	37	74.8	53.0	18.5	2.5	21.8	12.5	9.3

Table 1 also shows that body composition changes were marked and the post-expedition UWW measurements suggested body fat levels of around 2% compared to around 18.7% before departure. However, the technique assumes an unchanging density of lean tissues - an assumption that may be untrue under such extreme circumstances of weight loss.

b) *Energy expenditure using dietary intake/weight losses and the isotope-labelled water technique*

Estimates of energy expenditure from the dietary intakes and the UWW data gave mean values for the whole expedition of 29.0 MJ.day^{-1} in RF and 27.3 MJ.day^{-1} in MS. These were in good agreement with the overall estimates from the isotope-labelled water which gave mean values of 29.6 MJ.day-1 in RF and 24.1 MJ.day-1 in MS. However, although these figures are in themselves high, they actually masked exceptional values early in the journey. For the first 50 days, the energy balance data gave values of 32.8 MJ.day-1 in RF and 28.7 MJ.day^{-1} in MS, which were very similar to those from the isotope technique of 35.5 and 29.1 MJ.day^{-1} in RF and MS respectively. Furthermore, when estimates of energy expenditure from the isotope data were analyzed in 10 day periods, RF had an energy expenditure of 44.6 MJ.day^{-1} and MS of 48.7 MJ.day^{-1} between Day 20 and 30.

During the second part of the expedition, from Day 51 to Day 96, energy expenditures were much lower according to both the energy balance and isotope techniques giving values of 24.7 and 24.3 MJ.day^{-1} respectively for RF and 23.6 and 18.8 MJ.day^{-1} for MS. However, although lower values were expected at this stage, since sledges were lighter and the journey was partly downhill, the isotope estimates are difficult to trust since both men showed a surprising rise in urinary D and O18 levels at around Day 80. The isotope estimates for the entire second period were therefore based upon data for the limited period from 51 to 80 days. Since it is difficult to envisage why a change in enrichments of the natural background water source should have occurred beyond Day 80, the increases in D and O18 in both men can only be explained by the entry of isotopes from the breakdown of body tissues which do not usually exchange with body water at a significant rate. These must have then have either contained a "memory" of the higher background enrichments of the UK, or must have become "labelled" at the time of isotope dosing.

c) *Resting metabolic rates, and metabolic and biochemical responses to a high fat test meal before and after the expedition*

The measurements of resting metabolic rate before and after the expedition demonstrated unexpected changes with RMR kg^{-1} FFM increasing by 11.2% in RF and 8.8% in MS. The maximum metabolic responses to the test meal expressed as a percentage of RMR were also increased from 16.8% to 75.4% in RF and from 17.6% to 96.2% in MS.

The blood sampling following the test meal demonstrated some changes in the bodies fat and glucose handling with both men showing a more rapid appearance of circulating triglycerides after the expedition.

This suggests an improved fat absorptive capacity and post meal circulating gastro-intestinal peptide levels also rose to higher levels following the journey. RF showed evidence of increased insulin resistance with blood glucose levels rising to a maximum of 11.5 mmol.l^{-1} post-expedition, compared to 8.0 mmol.l^{-1} before.

d) *Maximum aerobic capacity and isometric muscle strength*

Following the expedition VO2 max. declined from 53.6 to 41.2 ml O_2 kg^{-1} min^{-1} in RF and from 58.1 to 46.0 ml O_2kg^{-1} min^{-1} in MS. The MVC force production measured in the different muscle groups had also declined by up to 19.9% in RF and 55.8% in MS (Table 2).

Table 2. Changes in maximal voluntary contraction kg isometric force production (dominant), pre- and post-expedition

	RF			MS		
	Pre	Post	% decline	Pre	Post	% decline
Elbow flextion	28.1	25.2	10.4	27.4	16.3	40.6
Elbow extension	23.2	18.6	19.9	20.2	14.7	27.2
Grip strength	46.1	45.4	1.5	64.9	40.9	27.0
Leg extension	121.1	113.8	6.0	192.1	85.0	55.8
Abdominal flextion	45.7	46.3	+1.3	52.5	42.7	19.7
Upright pull	144.7	131.1	9.3	183.2	113.0	38.3

e) *Skeletal muscle enzyme activity before and after the expedition*

The combination of relative undernutrition with the prolonged exercise produced some surprising changes in skeletal muscle biopsy samples taken from vastus lateralis pre- and post-expedition. These showed decreases in both cytoplasmic and mitochondrial enzyme activities of: 47% and 56% for glycerol-3-phosphate dehydrogenase (Gly3PDH); 49% and 18% for Hydoxy-acylCoA dehydrogenase (HAD); 35% and 13% for Citrate Synthase (CS); and 56% and 63% for Cytochrome oxidase (COX), in subjects RF and MS respectively (Table 3).

Table 3. Enzymes activities in vastus lateralis muscle biopsy samples taken pre- and post-expedition. Enzymes activities are pressed as nmol.min^{-1} kg^{-1} wet muscle at 25°C

	Glyc 3 P DH			HAD			CS			COX		
	Pre	Post	%Δ	Pre	Post	%Δ	Pre	Post	%Δ	Pre	Post	%Δ
RD 195	195	104	47	6.04	3.10	49	20.14	13.10	35	8.42	3.74	56
MS 216	126	96	56	5.86	4.91	16	23.33	20.22	13	7.48	2.80	63
Normal range	(146 - 370)			(4.6 - 8.7)			(10.6 - 37.6)			(7.00 - 25.00)		

Such decreases make an interesting contrast to increases of 20% to 80% that have been seen after 6 weeks of training with normal energy balance (Wibom et al, 1992) and together with the loss of muscle mass, probably caused the observed decline in isometric strength. However, it is not clear why MS should have suffered greater strength losses.

The decline in skeletal muscle mass and enzyme content also explain the decrease in maximal oxygen consumption since the capacity for peripheral utilisation would have been reduced. However, it is also likely that cardiac muscle was lost and that maximal cardiac output declined, changes that have been documented in man during less prolonged dietary restriction with a smaller deficit in energy intake vs. expenditure (Rahamadany et al, 1989).

f) *Changes in blood glucose, insulin, cortisol, growth hormone, protein and lipids at 10 day interval during the course of the expedition*

The blood samples taken during the expedition also yielded unusual results. During the expedition, end of day blood glucose levels were low with mean values of 3.0 mmol.l^{-1} in RF and 2.8 mmol.l^{-1} in MS, and on two occasions (days 70 and 95) both men were apparently grossly hypoglycaemic with values of around 0.3 mmol.l^{-1}. It is obviously tempting to assume that these very low values were artifactual, but on one occassion they were accompanied by a very raised growth hormone level which would be an appropriate response to hypoglycaemia. It would therefore appear that the prolonged exercise combined with the relatively low carbohydrate intake and the under-nutrition genuinely led to frank hypoglycaemia; and that the men had adapted to utilise ketones or other substrates in the CNS. Despite a daily intake of around 290g of mostly saturated fat, total cholesterol values remained esentially unchanged and HDL cholesterol rose in both men from pre-expedition levels of around 0.9 mmol.l^{-1} to post expedition values of around 1.6 mmol.l^{-1}. It would therefore appear that very high levels of exercise can offset the adverse lipid effects of even the most abnormal of diets.

DISCUSSION

It is evident from the weight losses alone, that this expedition entailed extremely hard work, maintained for a period of over 3 months. This exceptionally hard work resulted once again in massive exercise induced weight losses despite the very high energy intake. The magnitude of the changes in body composition were extreme in both men, and even the Minnesota experiment of Keys et al. (1950) only described changes of 70% in fatness and 20% in muscle mass after 52 weeks of chronic undernutrition. The very high energy expenditures documented by both the energy balance and isotope techniques must therefore be most unusual and, as far as I am aware, the isotope figures for the period between days 20 and 30, of 44.6 MJ.day^{-1} in RF and 48.7 MJ.day^{-1} in MS, are the highest sustained levels ever documented.

However, although these energy expenditure figures are exceptional and probably close to what is physiologically possible, they do remain lower than a theoretical energy expenditure ceiling of 58.5 MJ.day^{-1} that has been calculated as attainable by ultra-long distance runners (Davies and Thompson, 1979). They are also made more credible by their corresponding to the period when the heavy sledges were dragged uphill from the ice-shelf to the plateau. Later in the expedition, when the men were descending from the Polar plateau with lighter sledges, energy expenditures were nearer normal and the energy expenditure values for the overall journey do not look unreasonable considering the circumstances.

From the point of view of military relevance, it must be assumed that under extreme conditions, personnel could equal or even exceed these excessive values. They therefore raise some questions about the adequacy of military Operational Rations which rarely provide more than 23 MJ.day^{-1} - the figure consumed by the men on this expedition. However, noticeable debility did not occur on this Polar journey for at least 50 days and a reasonable level of function was maintained for approaching 90 days. It would therefore seem likely that major debility would not occur within the likely span of a military operation without resupply. Of course, ration restriction in the context of a military operation may be more extreme due to the need to backpack heavy loads, and it is not unusual for personnel to restrict their rations to around 10 MJ.day^{-1} for periods when carrying additional ammunition becomes the most critical consideration. However, even for this situation, the findings from the Polar expedition can be viewed as encouraging since between days 20 and 30 of the journey, deficits of the order of 20 MJ.day^{-1} were sustained whilst the men were working hard for prolonged hours each day.

According to the UWW, losses of body fat were extreme and anecdotally these losses were accompanied by a markedly lower resistance to the cold, although the exercise induced hypoglycaemia may also have disturbed effective thermoregulation. This, at first sight, would appear to raise the possibility that military clothing adequate for short-term cold weather operations may be potentially inadequate for very extended periods. However, the finding is not really transferable since the men on the trans-Antarctic expedition chose to carry very little insulative clothing, relying instead upon continued work to maintain body heat. They were able to do this since there was never any reason to stop other than at the end of the day when the protection of the tent

and sleeping systems was available. Military operators, on the other hand, will always have to be prepared for periods of low-level activity outside, and therefore will be obliged to carry some highly insulative protection.

Perhaps not suprisingly, weight changes also comprised considerable lean as well as fat losses, and in addition to this loss of muscle bulk, there were marked declines in muscle enzyme activities. It is therefore not surprising that there were decreases in both isometric strength and aerobic capacity, and it should be borne in mind that these measurements were made 7 days after completion of the journey when some recovery would have already occured. With almost all of their fat stores consumed, it would seem likely that even a short further period of negative energy balance would have precipitated a catastrophic decline in physical performance. However, although these findings suggest that strength losses detrimental to operational effectiveness will occur if military activities are protracted enough, once again, it seems unlikely that military personnel will reach this near terminal state of decline before dietary resupply was available. However, the figures do give Operational analysts some "maximal" data which might be useful in the consideration of very extreme scenarios.

The blood samples taken during the expedition yielded some very unusual results. It is obviously tempting to assume that the very low blood glucose values were artifactual, and certainly they may have been exaggerated by the cold causing low peripheral blood flows and hence greater peripheral glucose extraction. However, samples were taken in the tent which was not generally cold, and the low values were accompanied on one occasion in MS by raised cortisol and growth hormone levels which would be appropriate responses to marked hypoglycaemia and there was a general trend for increasing cortisol and GH levels throughout the expedition. It would therefore appear that the prolonged exercise, combined with the relatively low carbohydrate intake, did genuinely lead to severe hypoglycaemia and it suggests that, since they were conscious, the men may have adapted to the use of other substrates in the central nervous system. However, in the military context, the time for such an adaptation could not be relied upon and hence it is probable that the combination of large energy deficits with hard work would lead to severe hypoglycaemia. This should therefore be borne in mind when formulating lightweight Operational ration packs when there is the temptation to maximise fat content in order to minimise weight. On the other hand, the results from the expedition demonstrating adaptation to the high fat diet and no adverse changes in lipid profiles would encourage the use of Operational diets with higher than normal fat contents.

The insulin levels of around 11 to 14 $mIU.l^{-1}$ seen over the first 70 days of the expedition were rather high considering that glucose levels were 4.0 $mmol.l^{-1}$ or less. This may be due to a loss of insulin sensitivity secondary to the very high fat diet, although the insulin levels of 15 and 30 $mIU.l^{-1}$ in RF and MS respectively on Day 95 would still seem totally inappropriate in the face of glucose levels of only 0.3 and 0.4 $m.mol.l^{-1}$. Indeed, it would seem likely that this inexplicable hyperinsulinaemia was causing the hypoglycaemia.

The increased RMR and thermogenic responses following the expedition were in marked contrast to the changes that would be expected if similar weight loss had been induced by dietary restriction, when both parameters would have been likely to decline (Morgan, 1984). However, it has been shown that if "dieting" is accompanied by exercise, such reductions are limited and that if weight loss is achieved through increases in exercise whilst on a normal intake there are probably no declines at all (Mole et al. 1989). These data would therefore support a spectrum of change with RMR and DIT actually increasing if weight loss is induced by high levels of exercise during a period of high dietary energy intake.

The striking decline in testosterone in both men was similar, although more marked, to that reported by Aakvaag et al. (1978) in soldiers undergoing a combination of physical stress and near total sleep deprivation for 5 days. However, LH also declined during the Antarctic expedition, while Aakvaag reported little change or small increases in LH levels.

Overall, although there were only two subjects in these studies, the findings demonstrate that marked biochemical and physiological changes occur when men work hard in negative energy balance for a prolonged period. They therefore provide unique information regarding the body's adaptations under circumstances of extreme exercise and, since the men appeared to be close to likely physiological limits, they also give

indications regarding the period that well motivated men could sustain military effectiveness on inadequate rations. Certainly, it would be of great interest to obtain similar measurements on any future expedition of such duration and severity.

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